Light dark matter searches with positrons

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This LOI presents two complementary approaches to search for light dark matter with a multi-GeV energy positron beam. Light dark matter is a new compelling hypothesis that identifies dark matter with new sub-GeV "hidden sector" states, neutral under standard model interactions and coupling to ordinary matter through a new force. Accelerator-based searches at the intensity frontier are uniquely suited to explore the dark sector.
Using a high-intensity and high-energy positron beam, and exploiting a novel light dark matter production mechanism—positron annihilation on atomic electrons—the proposed experiments will be able to explore new regions in the light dark matter parameter space, confirming or constraining the hypothesis.

Introduction

In recent years, a novel hypothesis for the nature of dark matter (DM) has been introduced. It predicts the existence of **light dark matter** (LDM) particles, with sub-GeV mass, interacting with standard model (SM) states through a new force. The simplest such model predicts LDM particles (denoted χ) with masses below 1 GeV, charged under a new force and interacting with SM particles via the exchange of a light spin-1 boson, usually referred to as "heavy photon" or "dark photon" (A') (1–3). This picture allows for an entire new "dark sector" containing its own particles and interactions and is further compatible with the well-motivated hypothesis of DM thermal origin (4). This hypothesis assumes that, in the early Universe, DM and SM abundances reached thermal equilibrium through an annihilation mechanism. The present DM density, deduced from astrophysical measurements, is thus a relic remnant of its primordial abundance (4). The thermal origin hypothesis provides a relation between the currently observed DM density and the model parameters, resulting in a clear, predictive target for discovery or falsification (5).
This constraint, within the minimal A' model, is valid for every DM and mediator variation up to order-one factors, pro-

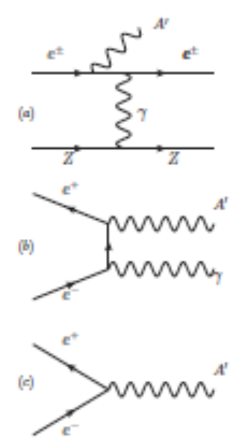

Fig. 1. Three different A' production modes in fixed-target lepton beam experiments: (a) A'-strahlung in e^-/e^+-nucleon scattering; (b) A'-strahlung in e^+e^- annihilation; (c) resonant A' production in e^+e^- annihilation.

vided that $m_{\mathrm{DM}} < m_{\mathrm{MED}}$.

Dark sector searches with positron beams on fixed targets

LDM particles can be produced in collisions of electrons or positrons of several GeV with a fixed target by the processes depicted in Fig. 1, with the final state A' decaying to a $\chi\bar{\chi}$ pair. For experiments with electron beams, diagram (a), analogous to ordinary photon bremsstrahlung, is the dominant process. However, for thick-target setups (where positrons are produced as secondaries from the developing electromagnetic shower), it has been recently shown that diagrams (b) and (c) actually give non-negligible contributions to select

Light Dark Matter searches with positrons

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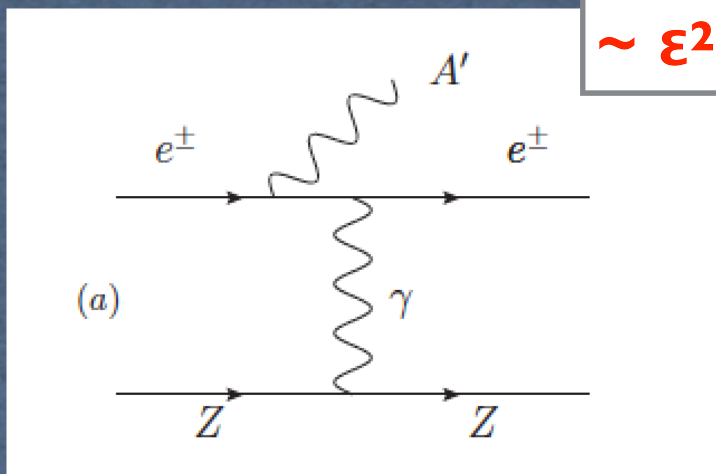
(on behalf of JPOS Collaboration)

Outline

- Physics motivations
- Work plan & paper
- Snowmass expected outcome

A' Production mechanisms - e$^{\pm}$

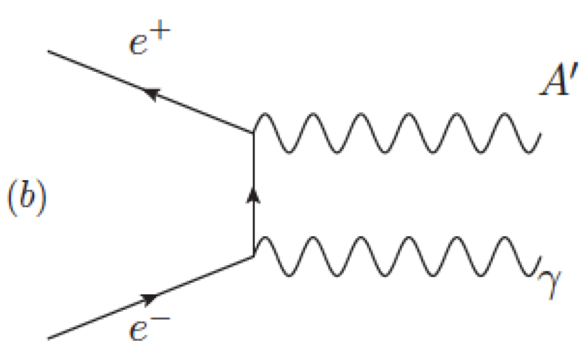


~ $\varepsilon^2 \alpha^3$

The Weizsacker-Williams approximation (*A'-strahlung*)

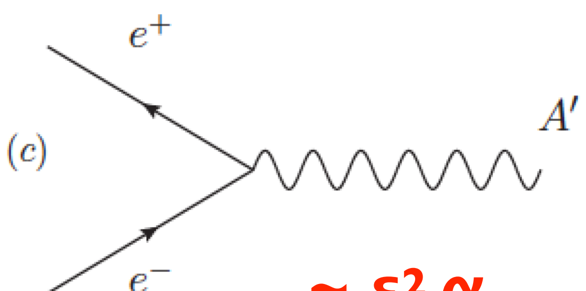
- The incoming electron 'see' a fast-moving cloud of effective photons to scatter from
- Photons are almost on-shell (low Q2) → transverse photons ~ e$^-$ γ_{Real} scattering
- Same treatment as the regular *bremstrahlung*
- Regularisations occurs in the case of interest $M_{A'} >> M_{e-}$
- Effective photon flux χ is critical, accounting for nuclear effect using FF

A' Production - positrons



~ $\varepsilon^2 \alpha^2$

- **NON-RESONANT annihilation**
  - **A' along (e$^+$e$^-$) direction**

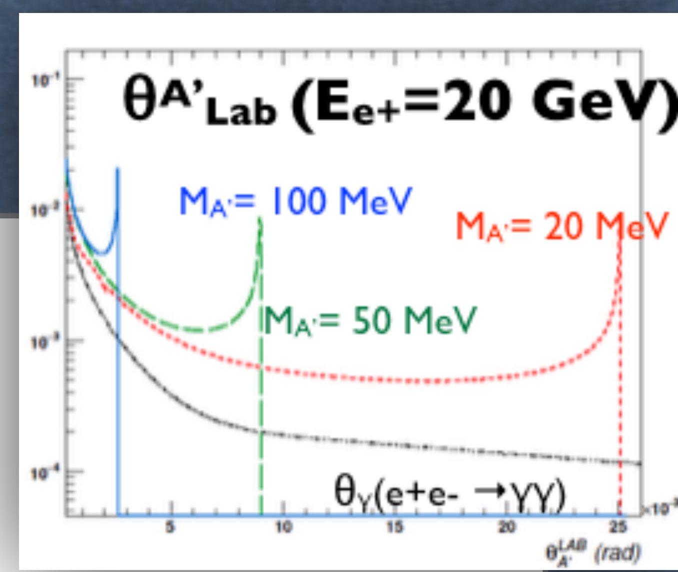


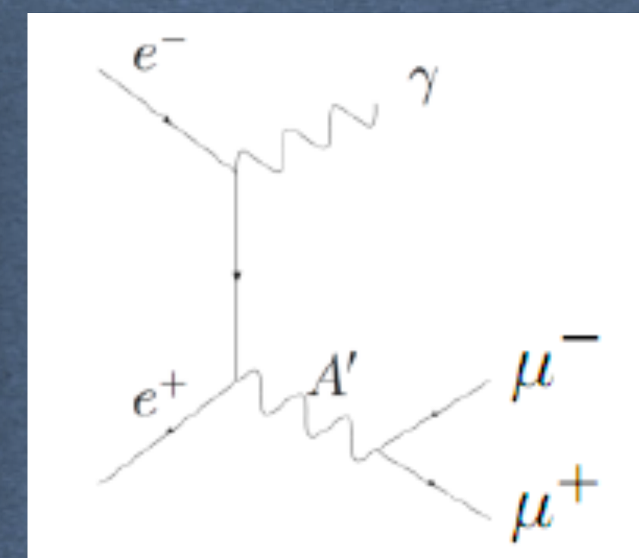
~ $\varepsilon^2 \alpha$

- **RESONANT annihilation**

$$\sigma_r = \sigma_{\rm peak} \frac{\Gamma_{A'}^2/4}{(\sqrt{s} - m_{A'})^2 + \Gamma_{A'}^2/4},$$

- **Two-body process**
- **A' forward-peaked along e$^+$ direction**
- **$E_{A'} = E_R = m^2_{A'}/2m_e$**



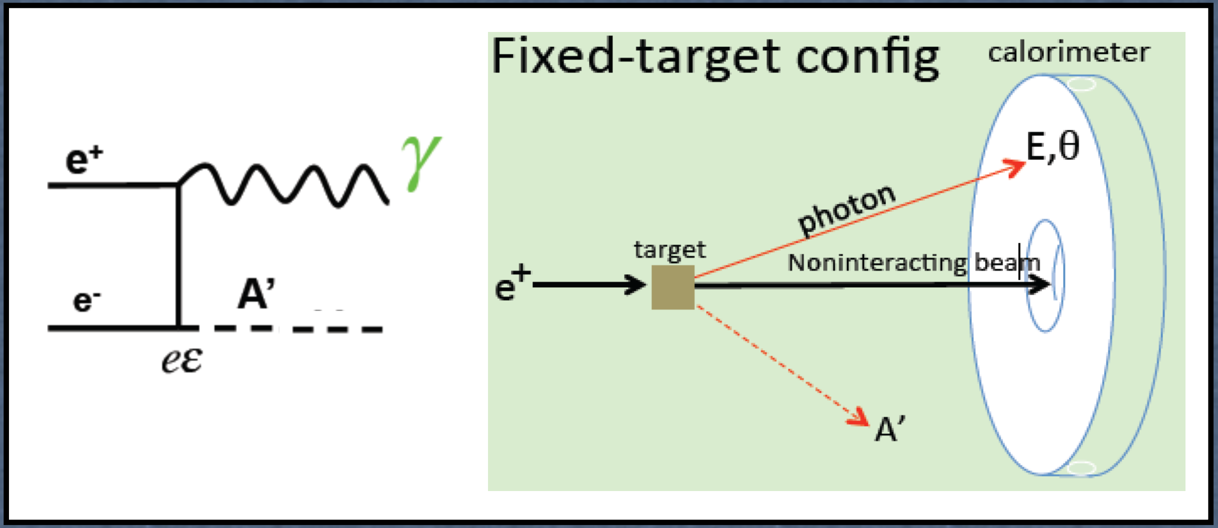


- Known and used
- Collider (missing mass experiments)
- Thin target experiments (visible decay)

e+e- → γ' γ → μμ γ

→ **BABAR, BELLE, KLOE, CLEO**

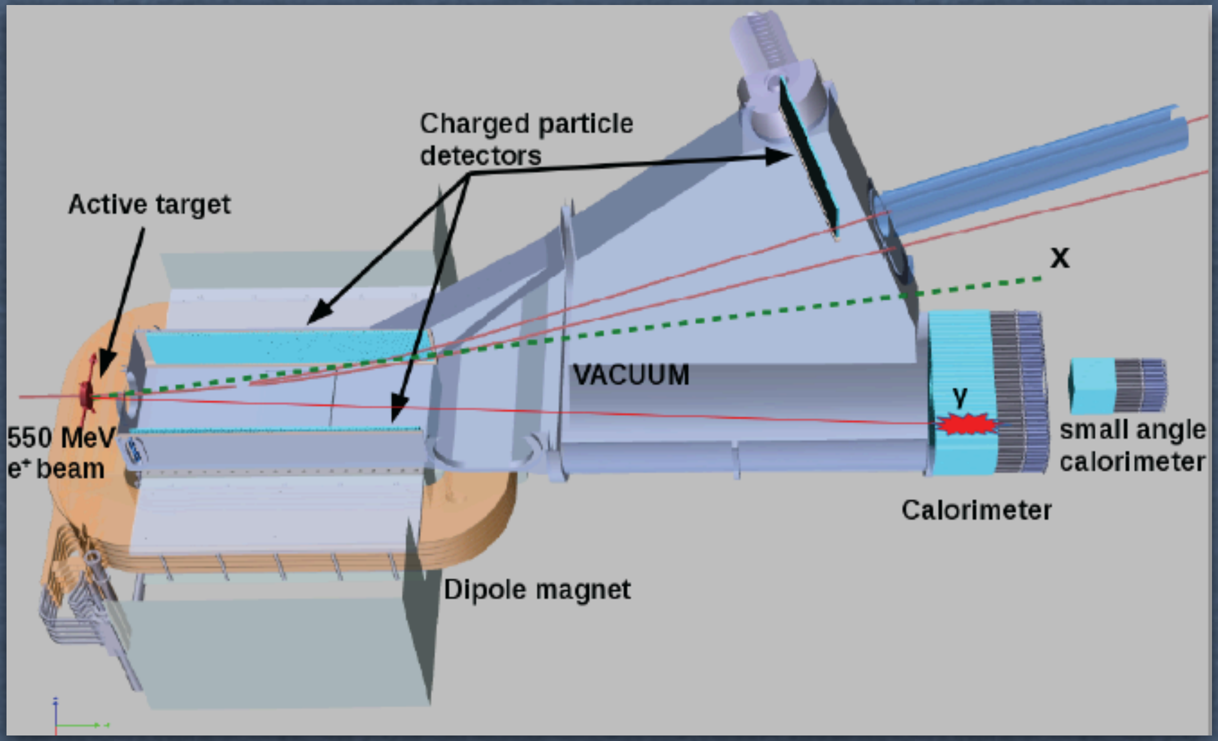
e^+ annihilation on fixed (thin) target - invisible -



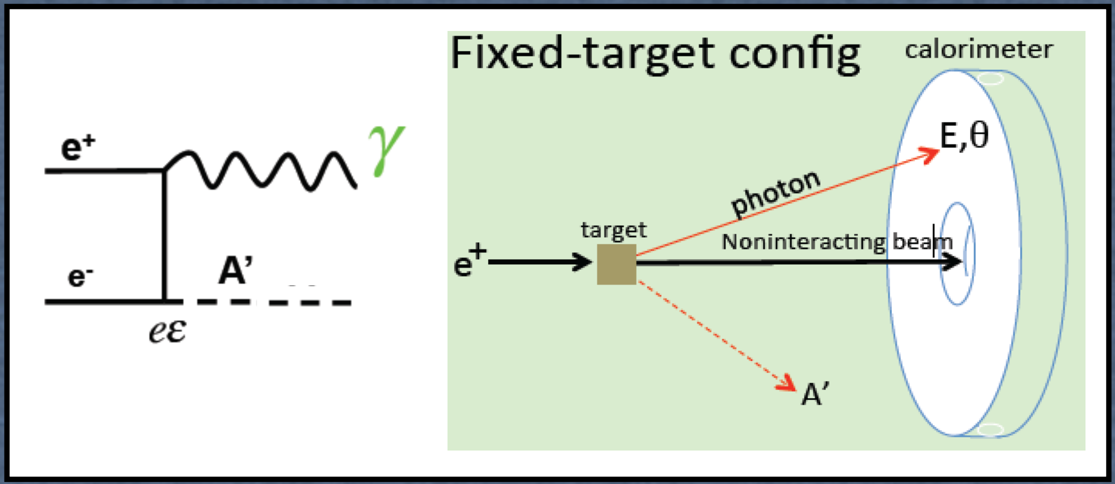
Missing mass search:
- Independent of A' decay mechanism
- Bump hunt (monophoton@collider)
- Need a positron beam
- Limited $M_{A'}$ accessible
  - 1 GeV beam: $M_{A'} < 31$ MeV
  - 5 GeV beam: $M_{A'} < 71$ MeV

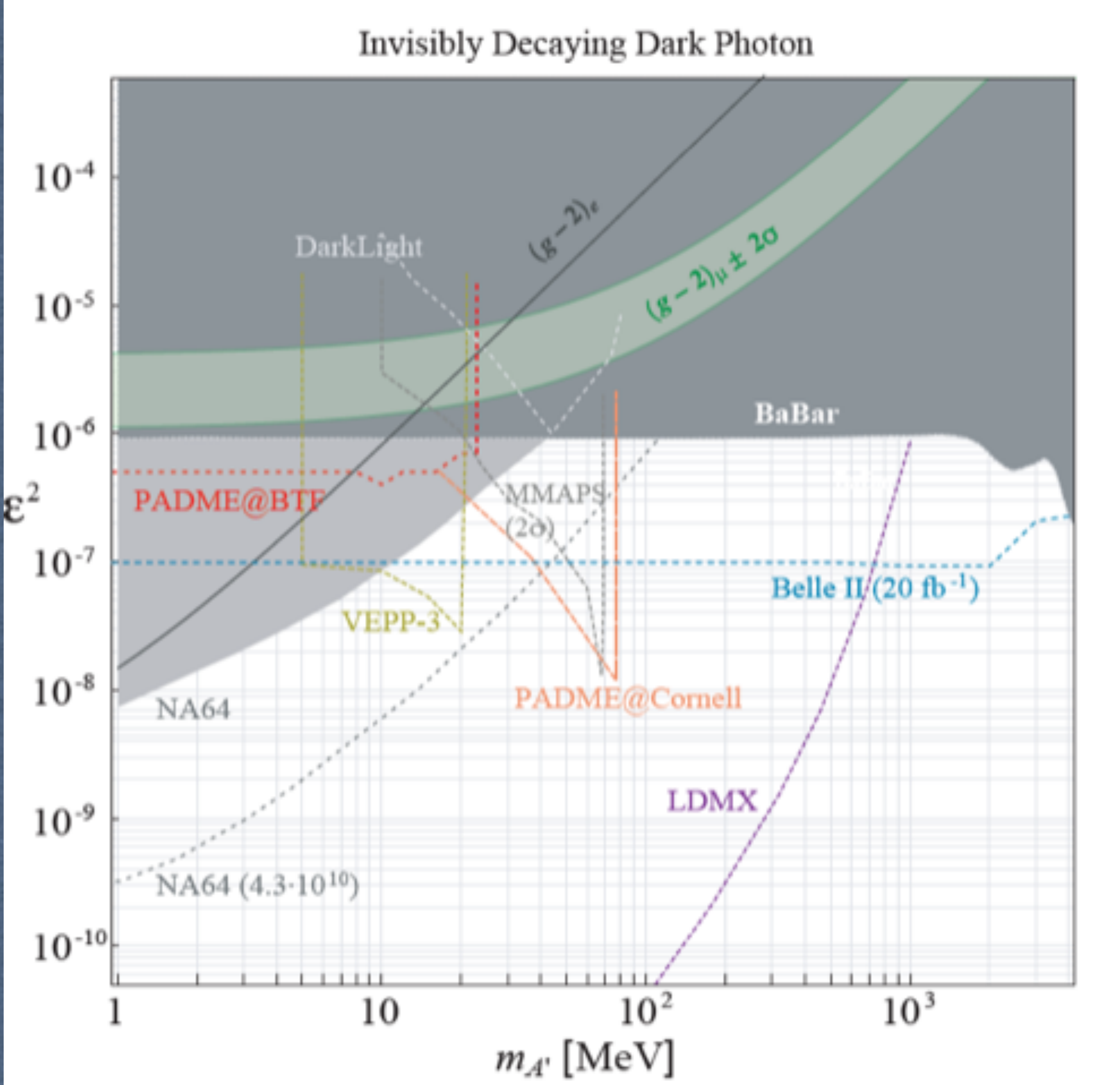
PADME@LNF

- **Beam**: e+ form LNF LINAC, 550MeV, multiplicity ~ 20k e+/ bunch, bunch duration 250 ns, frequency 49 Hz.
- Diamond active **target** 100 μm thickness: position, size and intensity of incoming beam
- Dipole **magnet** of 0.45 T to deflect charged particles out calorimeter
- Plastic scintillators **veto** system + high energy positron veto in order to detect charged particles bent by magnet
- Electromagnetic calorimeter (**ECAL**) composed of 616 BGO crystals
- Small angle calorimeter **(SAC)** composed of 25 PbF2 crystals
- Already collected 5 10^{12} POT (expected 10^{13} POT)



e^+ annihilation on fixed (thin) target - invisible -





VEPP3
- E_{e+} = 500 MeV
- EOT ~ 10^{15} - 10^{16} year^{-1}

LNF
- E_{e+} = 550 MeV
- EOT ~ 10^{13} - 10^{14} year^{-1}

Cornell
- E_{e-} = 5.3 GeV
- EOT ~ 10^{17} - 10^{18} year^{-1}

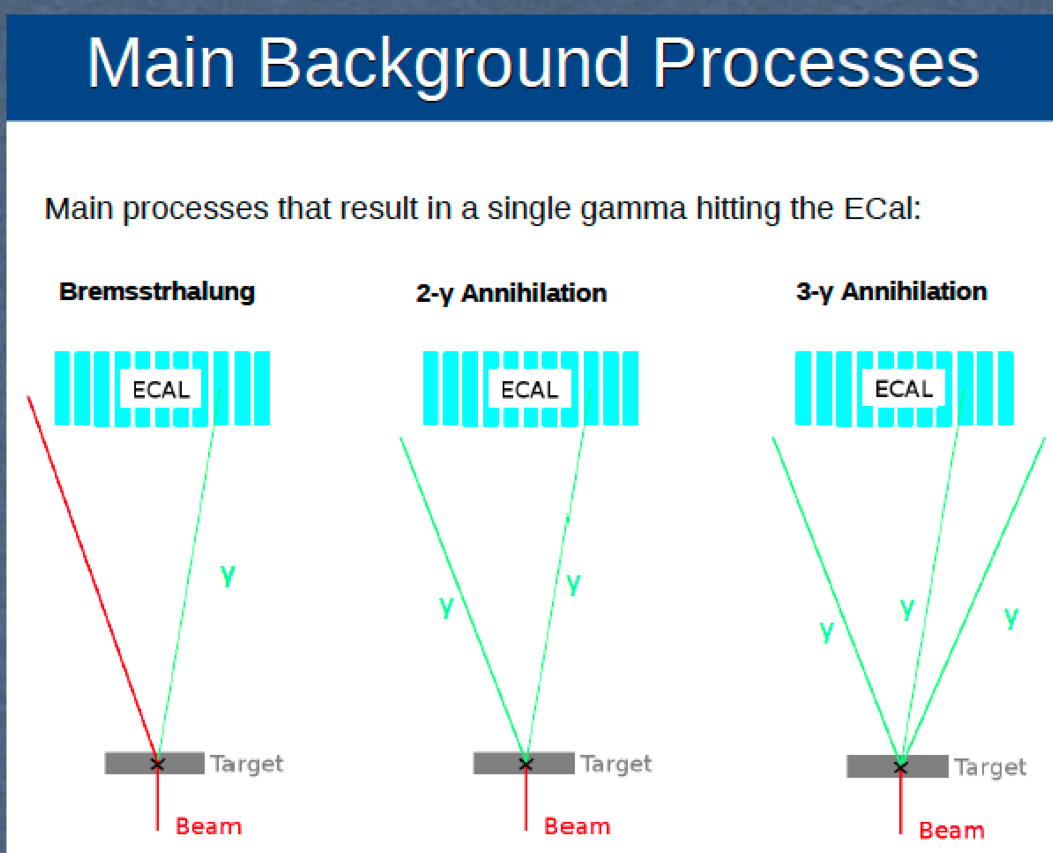
JLab (future)
- E_{e-} = 11 GeV
- EOT ~ 10^{18} - 10^{19} year^{-1}

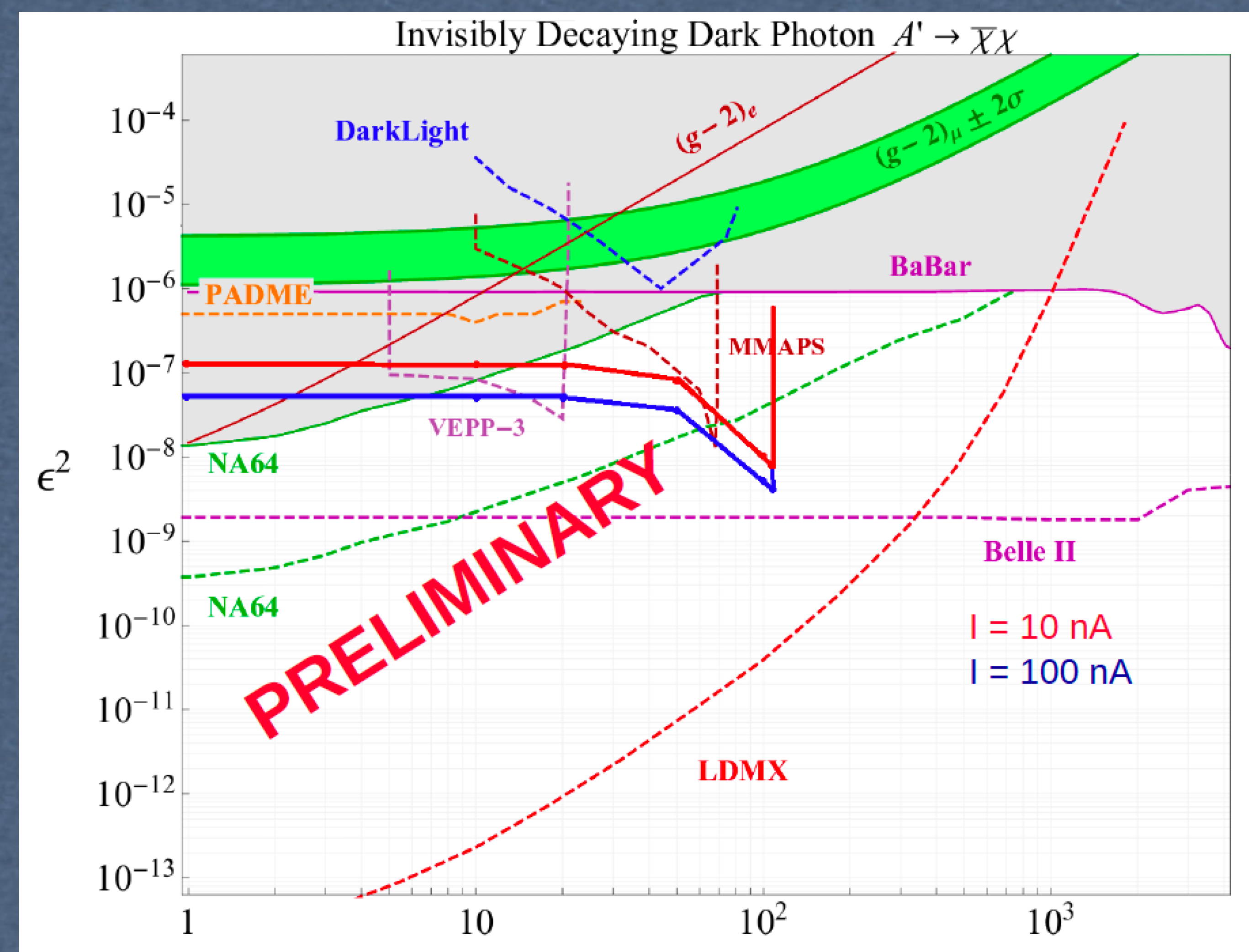
PADME@JLAB

Reusable PADME components:
- Target - PADME carbon target can be installed at CEBAF
- Calorimeter - PADME Ecal meets all requirements of the experiment (energy resolution, angular resolution, size)
- Veto System - technology and front-end electronics from PADME veto can be reused

New equipment:
- DAQ system - suitable for a CW beam

- Main limitation: limited energy in the CM ~ sqrt(E_{beam})
- High energy positron beams are not (yet) available
- The highest energy at JLab (~11 GeV) Max $M_{A'}$ ~ 106 MeV

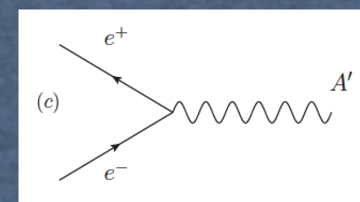




Positrons@beam-dumps

- An electromagnetic shower is a powerful source of positrons!

$$N_{A'} = \frac{N_A}{A} Z \rho \int_{E^R_{min}}^{E_0} dE_e \, T_+(E_e) \, \sigma(E_e) \; ,$$



for RESONANT annihilation and Γ smaller than T_+ variation

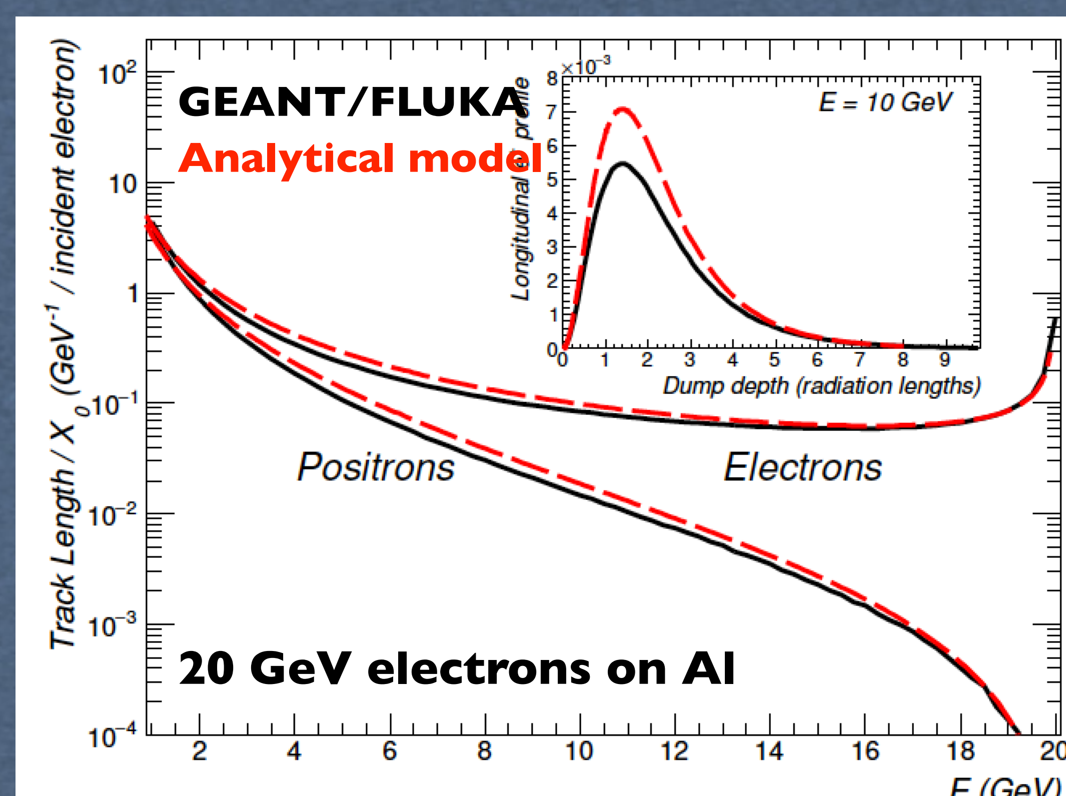
$$N_{A'} \simeq \frac{\pi}{2} \frac{N_A}{A} Z \rho \, \sigma_{\text{peak}} \Gamma_{A'} \frac{m_{A'}}{m_e} T_+(E_R)$$

Track-length $T_+(E)$: integral of positron fluence over the beam-dump volume

- density of particles in the volume
- path length of a positron in the BD with energy between E and E+dE
- I^+_e = differential energy distribution (positron current)

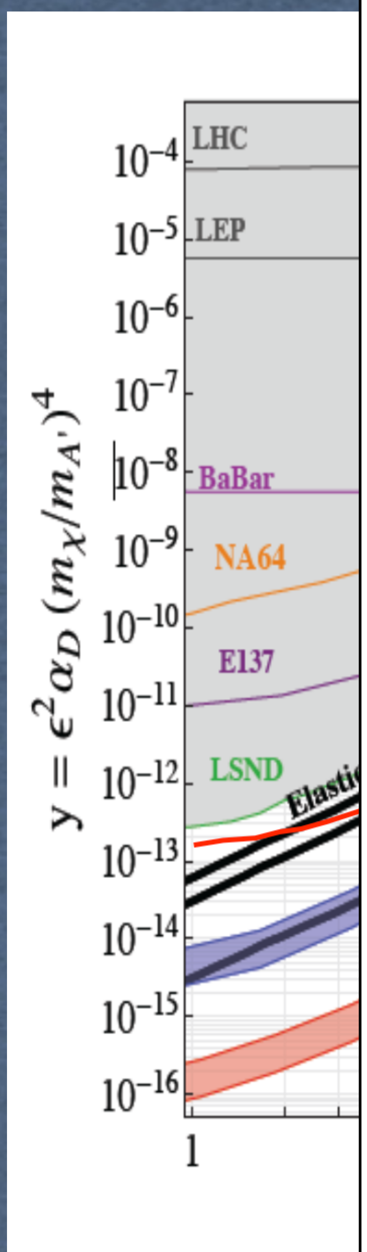
$$T_+(E) = \int_0^{L_{Dump}} I_e^+(E_e, t) dt$$

$T_+(E)$ can be evaluated analytically or by simulations (GEANT4) sampling the shower profile at different depth in the BD

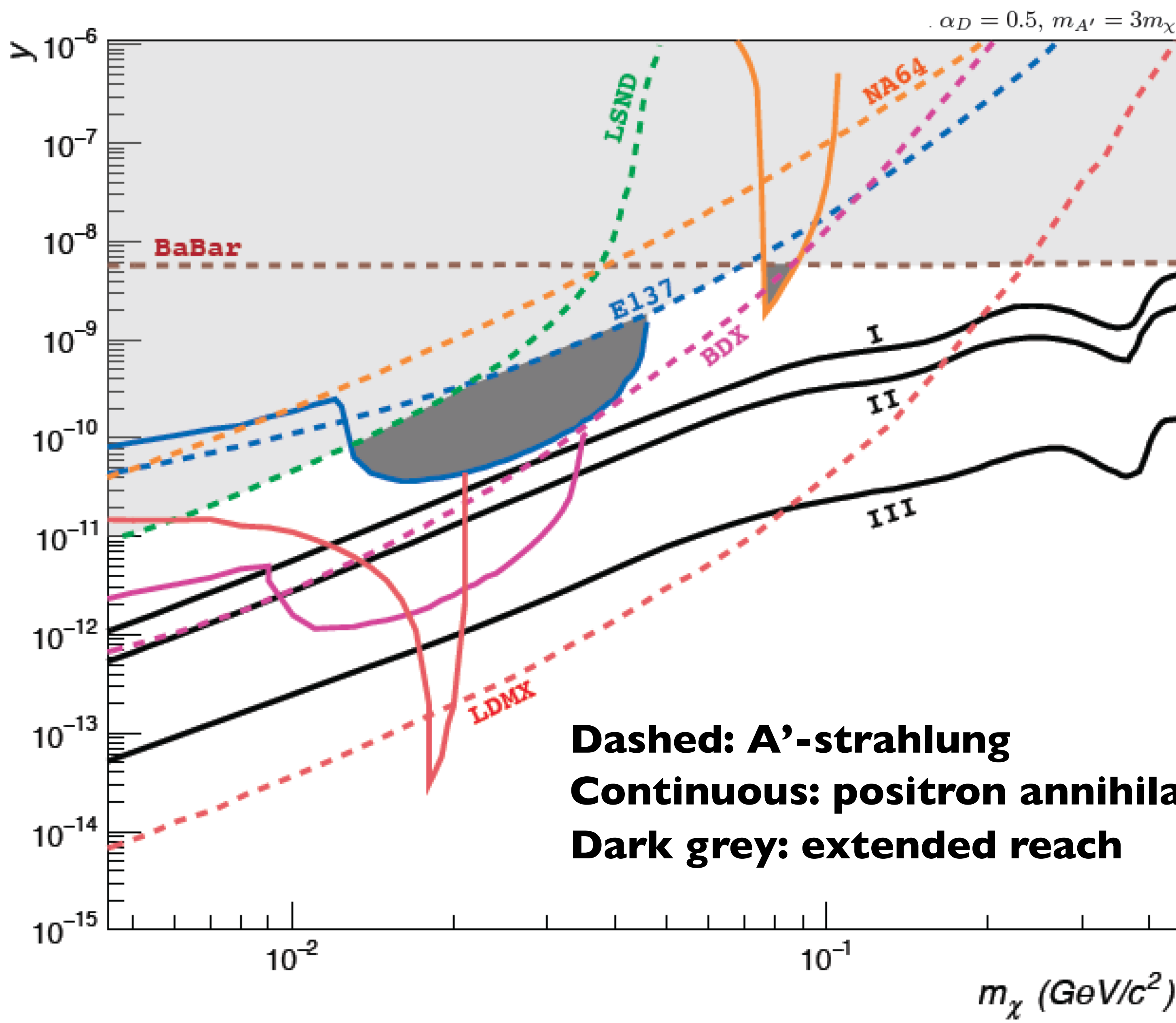


Good agreement (high energy) with analytical calculation by Y. S. Tsai and V. Whitis, Phys. Rev. 149, 1248 (1966)

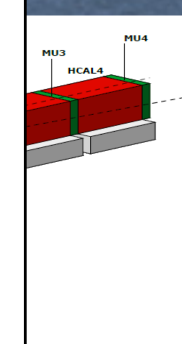
Effects on current exclusion limits (BD - invisible)



Inclusion of e⁺ annihilation lowers the exclusion limits by x10 in 20 MeV < $M_{A'}$ <40 MeV



decay search



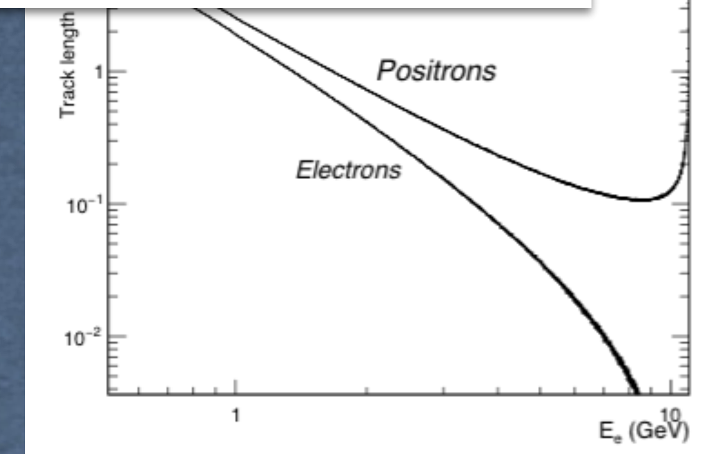
riments

S-II 4 GeV e-

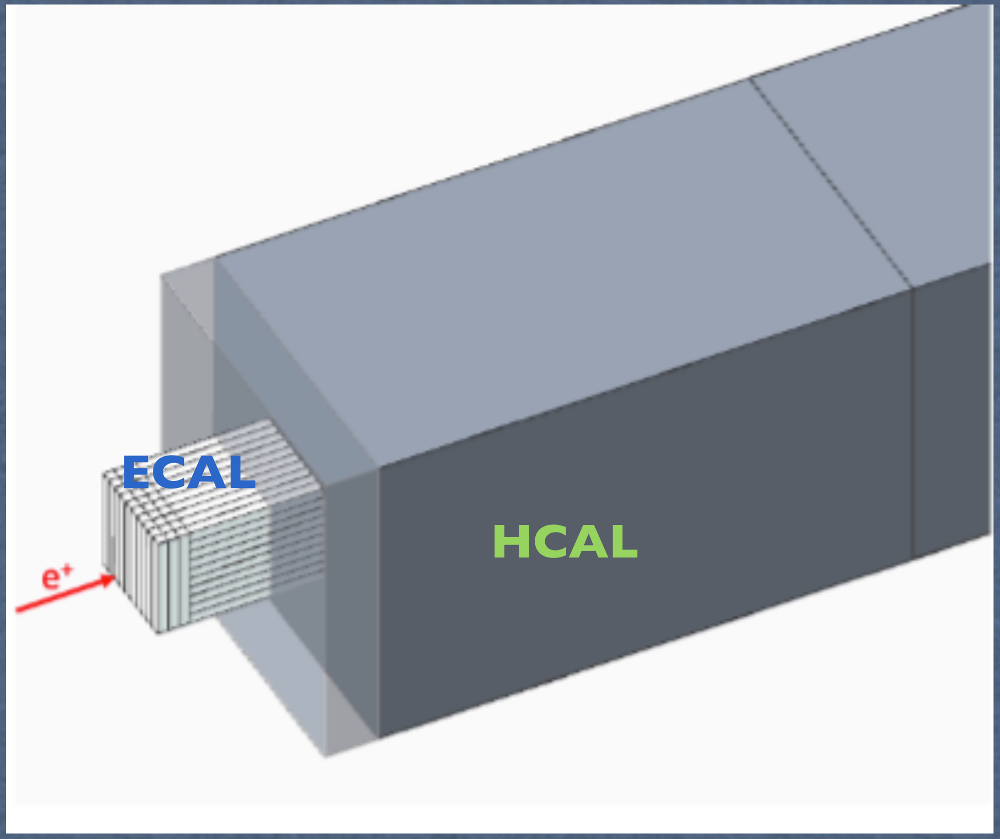
eam with 10^{22}

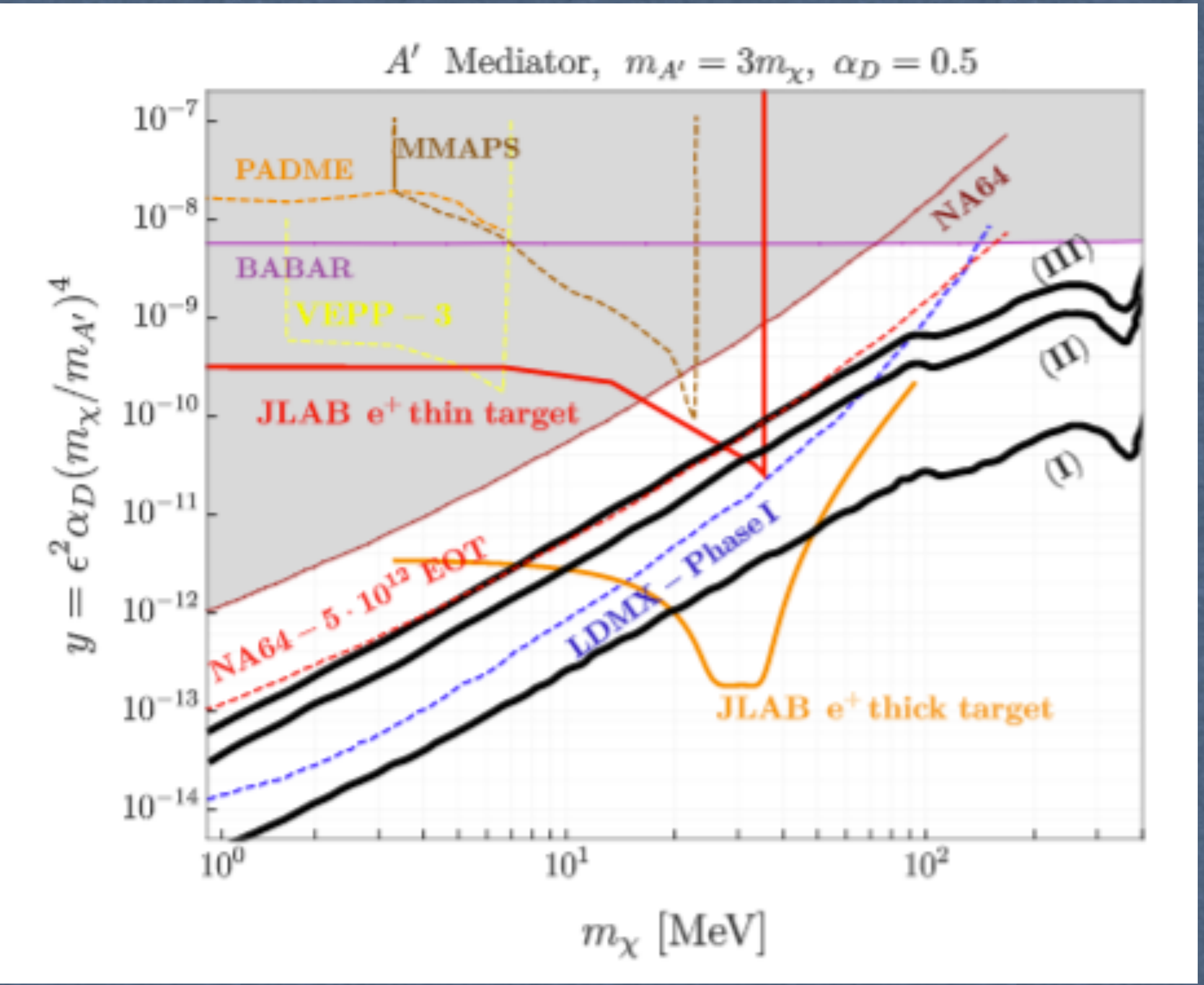
e^+ annihilation on fixed (thick) target - invisible -

$$N_s = n_{POT}\frac{N_A}{A}Z\rho\int_{E_{miss}^{CUT}}^{E_0} dE_e\, T_+(E_e)\sigma(E_e)$$



- *Active* beam-dump experiment (*á la* NA64 but with positron!)
- Clear signal (peak!) due to the annihilation: $M_{A'} = \mathrm{Sqrt}(2\ m_e\ E_{miss})$
- Missing energy exp (e+ Z → e+ Z' A' with A' → invisible)
- 11 e+ beam, low current
- Active target (calorimeter)
- Exclusion plots based on 10^{13} POT
- Detector: ECAL to measure e+; HCAL to veto





Workplan	Completion	
Study a JPOS program with an optimised e+ beam (future)	in progress	By June 2021
Explore existing secondary positron beams at Jefferson Lab	in progress	
Adapt the existing equipment to JPOS program	in progress	
Write e LOI/Proposal for JLab PAC49 for primary/secondary beams	in progress	
Start an R&D program (detector and simulations) to assess the best detector technology, background, …	future	After June 2021

- ✳ JPOS has strong potential to search for LDM in a new way
- ✳ Contributed paper ready for June 2021 (target)
- ✳ Between now and Snowmass: define the JPOS program with primary (future) and secondary (near) positron beams at JLab
- ✳ Expected Snowmass outcome:
  recognise the great potentiality of light dark matter searches by using positron beams